INFLUENCE OF A STREAM PERTURBATION BEFORE THE SKIMMER ON MOLECULAR-BEAM PARAMETERS

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Molecular-beam formation from a supersonic rarefied gas flow by using the method of [1] is accompanied by interaction between the free stream and a conical intake (skimmer) [2]. According to modern conceptions [3], such interaction can be separated conditionally into external and internal. The external skimmer interaction is understood to be the process of scattering the freestream particles by molecules reflected from the outer surface of the skimmer and the forming of a diffuse gas cloud or a detached shock depending on the flow conditions. The internal skimmer interaction is due to collisions between the beam molecules themselves, with the internal surface, and with the residual gas behind the inlet section of the skimmer.

In existing models of skimmer interaction ([3-5], for example) the main role in the skimmer flow mode going over from the continuous to the free molecule flow is assigned to the external interaction. In practice, it is impossible to determine the role of the external and internal interactions separately in experimental investigations of skimmer interaction by the traditional method, i.e., by measuring the parameters in the molecular beam during variation of the freestream conditions and the skimmer geometry.

The purpose of this paper is to investigate the influence of the external skimmer interaction on the molecular beam parameters by simulating the dissipating cloud ahead of the skimmer by a plane shock.

The investigations were performed on the low-density gasdynamic apparatus of the Institute of Thermophysics of the Siberian Branch of the Academy of Sciences of the USSR, equipped with a molecular-beam system [6]. The diagram of the experiment is presented in Fig. 1, The conical skimmer of a small molecular-beam generator is placed in a free nitrogen jet 1 at a fixed distance x from the exit of the acoustic nozzle 2. The nozzle d_* and skimmer d_s diameters were 2.11 and 0.81 mm, respectively. A special shock holder 6 was mounted ahead of the inlet edge of the skimmer on the hollow cylindrical insert 4 between the base 5 and the nose 3 of the skimmer in order to form a shock. The shock holder was moved along the skimmer axis during the experiments, whereby a change in the parameters at the inlet edge due to the unperturbed flow conditions to a position behind the shock front 7 was assured. Each experiment mode was reproduced twice: First the gas density ahead of the skimmer inlet edge was measured by using electron-beam diagnostics [7] (the electron beam is shown in Fig. 1 by the line of double dashes 8), and then the velocity distribution function of the molecules in the beam by the transit-time method [6].

Two series of measurements were conducted at the nozzle–skimmer (or nozzle–electron beam) spacings $x/d_* = 55$ and 75 for constant stagnation pressures and temperatures ($p_0 = 350$ mm Hg and $T_0 = 293°K$). Results of measuring the normalized density in the stream ahead of the skimmer n/n_∞ are presented in Fig. 2a as a function of the shock location relative to the electron-beam axis $l = 0$. That location of the shock holder at which the density at the measurement point n differed by 0.5% from its limit value in the absence of a shock n_∞, i.e., $n/n_\infty = 1.005$, was selected as the value of ~1 mm. The visible electron-beam diameter in the measurements was ~1 mm. The skimmer was at a distance 4 mm downstream in order to eliminate the contribution of the luminescence occurring during the electron-beam interaction with the skimmer from the signal being recorded. This introduced no noticeable changes in the shape of the shock, since the skimmer exerts practically no influence on shaping the latter. It is seen from Fig. 2a that the shock formed by the shock holder yields a maximum drop in the density of approximately six times, as should be expected. The shock becomes more extended with increasing distance from the nozzle.

The dependence of the density on the molecular-beam axis on the coordinate l is represented in Fig. 2b. The skimmer was moved 4 mm upstream in the molecular-beam measurements so that the inlet edge of the skimmer would be at the same distance from the nozzle as the axis of the electron beam. The molecular-beam density n_b calculated as the zero-initial-time velocity distribution function is also normalized to one at $l = 0$.

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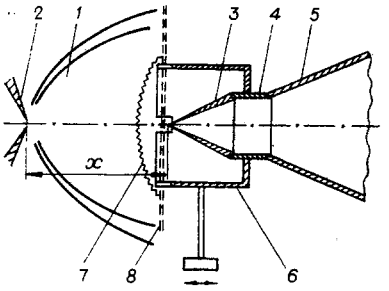

Fig. 1

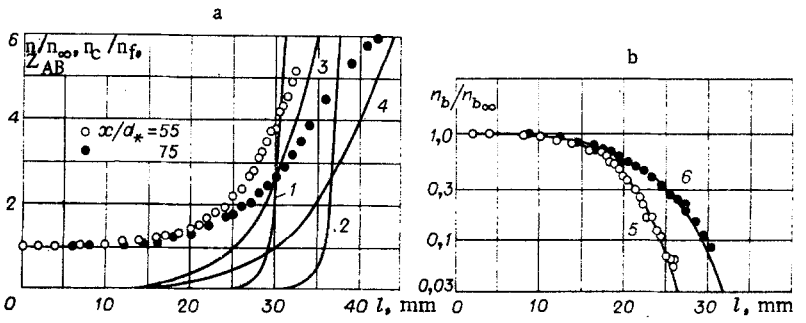

Fig. 2

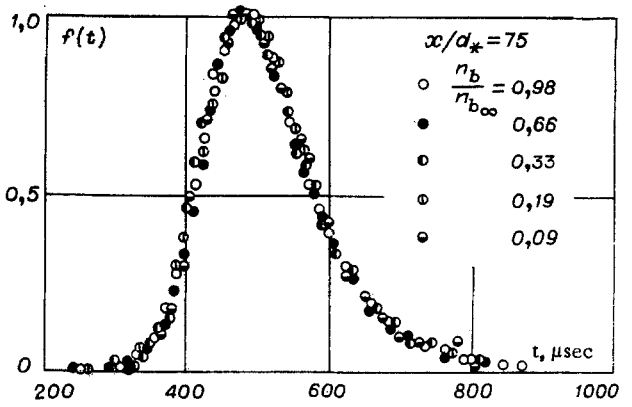

Fig. 3

It can be seen that as the density rises ahead of the skimmer edge, the density being recorded on the molecular-beam axis drops.

The form of the molecule velocity distribution functions, normalized to one at the maximum, is shown in Fig. 3 ($x/d_* = 75$) as a function of the transit time t for several values of the molecular-beam density. It follows from the results presented that the form of the normalized molecule velocity distribution function being recorded in the molecular beam, and, therefore, also the normalized moments of this function (the translational temperature and velocity) does not vary under the conditions of freestream scattering by the gas cloud (shock) ahead of the skimmer, while the molecular-beam density drops by more than an order of magnitude. In our opinion, the establishment of this fact is the main result obtained in experiments with a shock holder.

The following deductions can be made on the basis of the experimental dependences obtained: 1) The main contribution to the signal at the detector of a molecular beam is from the freestream particles which do not undergo collisions in the gas cloud ahead of the skimmer; 2) for the velocity under study, the dependence of the total scattering cross section on the relative molecule velocity is inessential within the limits of measurement error.

In order to explain the results obtained, let us make some estimates. The contribution to the signal at the molecular-beam detector from the freestream particles n_f and the gas cloud particles n_c can be determined by means of formulas presented in [8]. The results of such an estimate are presented in Fig. 2a (curves 1 and 2 are for $x/d_* = 55$ and 75, respectively). The ratio n_c/n_f grows rapidly with the increase in the density of the scattering gas; however, the scattering gas cannot introduce an essential contribution to the signal being recorded in the whole range of values of l where the molecule velocity distribution function is recorded successfully.

Let us estimate the mean number of collisions by one freestream molecule (a particle of species A) with the gas cloud molecules (particles of species B). Under the assumption that the scattering gas molecules have acquired the temperature behind the shock ($T_B = t_2$) and the freestream molecules have the limit velocity, this number can be determined by the formula [9]

$$Z_{AB}(l) = \pi d_m^2 n_\infty \sqrt{1 + v_B^2/v_A^2} \int_0^l (n_b(l)/n_\infty)\, dl,$$

where $d_m = 3.62 \cdot 10^{-8}$ cm is the molecule diameter [9], $v_B = \sqrt{8kT_2/\pi m}$; k is the Boltzmann constant, and m is the mass of a molecule. The results of computing Z_{AB} are presented in Fig. 2a (curves 3 and 4 are for $x/d_* = 55$ and 75, respectively). As should have been expected, the number of collisions Z_{AB} grows sharply on the section with the steep rise in the density n/n_∞; however, Z_{AB} does not exceed 1.0-1.5 in that region where the molecular-beam parameters were recorded.

The estimates made show that the number of second etc. collisions capable of returning the scattered molecules back into the beam is small. Therefore, any collision of freestream molecules with the scattering gas will result, in practice, in knocking molecules of the species A out of the limits of the solid angle Ω_d within which particles moving rectilinearly can fall from the skimmer to the detector (in this paper $\Omega_d \simeq 3 \cdot 10^{-4}$ sr).

In this case, a change in density on the molecular-beam axis should be described by an exponential scattering law:

$$n_b(l)/n_{b\infty} = \exp\,[-qn_s(l)l], \tag{1}$$

where q is the total beam absorption section, n_s is the density of the scattering gas, and l is the spacing at which scattering occurs. Since the density n_s depends on l, formula (1) is converted into the form

$$n_b(l)/n_{b\infty} = \exp\left[-qn_\infty \int_0^l ((n(l)/n_\infty) - 1)\, dl\right] \tag{2}$$

under the assumption that the density of the scattering particles can be determined from the results of measuring the density ahead of the skimmer inlet section, $n_s(l) = n(l) - n_\infty$. Using the value of the total absorption section obtained in [10] and the parameters n_∞ and $n(l)/n_\infty$ from the present experiments, the change in molecular-beam density as a result of scattering by the gas cloud ahead of the skimmer can be estimated by means of (2).

The results of such estimates are superposed by solid lines in Fig. 2b (curves 5 and 6 are for $x/d_* = 55$ and 75, respectively). Good agreement between the computations and the experimental results confirms the validity of the assumptions made and affords the possibility of estimating the drop in density in a molecular beam because of a gas cloud ahead of a skimmer by using (2).

It has therefore been established that conditions exist under which the external skimmer interaction does not distort the normalized freestream molecule velocity distribution function. Among such conditions are a small detector solid angle and a mean number of freestream molecule collisions with the scattering gas $Z_{AB} \leq 1$. The results obtained show that there is no need for high demands on the quality of leading edge and outer surface fabrication for the skimmer in distribution function measurements. The distortions in the distribution earlier in molecular-beam formation [3] by using a skimmer are due principally to processes occurring downstream of the skimmer inlet section, i.e., to the internal skimmer interaction.

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SIMPLE WAVE EQUATIONS OF ONE-DIMENSIONAL MOTION OF A GAS – DUST MIXTURE

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§1. The equations of one-dimensional nonstationary motion of a gas–dust mixture [1] can be written in the following form:

$$\frac{\partial}{\partial t} v_1 - \frac{\partial}{\partial \xi} u_1 = 0, \tag{1.1}$$

$$v_1 \frac{\partial}{\partial t} v_2 + (u_2 - u_1) \frac{\partial}{\partial \xi} v_2 - v_2 \frac{\partial}{\partial \xi} u_2 = 0, \quad \frac{\partial}{\partial t} u_1 + \frac{\partial}{\partial \xi} p = -v_1 f_{12},$$

$$v_1 \frac{\partial}{\partial t} u_2 + (u_2 - u_1) \frac{\partial}{\partial \xi} u_2 = v_2 v_1 f_{12},$$

$$v_1 \frac{\partial}{\partial t} p + \gamma p \frac{\partial}{\partial t} v_1 = (\gamma - 1) v_1 f_{12} (u_1 - u_2) - \beta_1 (T_1 - T_2),$$

$$v_1 \frac{\partial}{\partial t} T_2 + (u_2 - u_1) \frac{\partial}{\partial \xi} T_2 = \beta_2 v_1 (T_1 - T_2),$$

$$v_1 d\xi = dx - u_1 dt,$$

where u_i, v_i, and T_i are the velocities, specific volumes, and temperatures of the phases (the subscript 1 refers to the parameters of the gas); p is the pressure; f_{12} is the volumetric force due to the interaction between the gas and the particles as a result of frictional forces; and γ is the ratio of the specific heat capacities of the gas. The coefficients β_i have the form

$$\beta_1 = \frac{6(\gamma - 1) v_1}{\rho_2^0 d v_2}, \quad \beta_2 = \frac{6}{\rho_2^0 d c_2} \alpha, \quad \alpha = \frac{\lambda_1}{d} \mathrm{Nu},$$

where ρ_2^0 is the true density of the second phase, d is the diameter of the particles; λ_1 is the thermal conductivity; and Nu is the Nusselt number. The terms reflecting the force interaction and thermal interaction between the phases are expressed in concrete form as follows [2]:

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